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Instrumentation is requested for probing the surface morphology and composition of electronic/optical materials with Air Force applications. This instrumentation is needed for development of advanced materials processing methods for new RE/optical and infrared devices. The Air Force needs for such devices are in 1) optically controlled phased array radar or in optical transmission of RF signals and 2) mid-IR countermeasure systems. The requested items fall into two categories: instrumentation for imaging of etched or ion-sliced ferroelectric surfaces and instrumentation for in situ diagnostics of infrared materials being etched or surface passivated in a UHV environment. The instrumentation will be used in a large multidisciplinary laboratory with a proven record of research and collaboration with DoD laboratories and industries.

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Final Report

I. Request for Instrumentation

A) Abstract

Instrumentation is requested for probing the surface morphology and composition of electronic/optical materials with Air Force applications. This instrumentation is needed for development of advanced materials processing methods for new RF/optical and infrared devices. The Air Force needs for such devices are in 1) optically controlled phased array radar or in optical transmission of RF signals and 2) mid-IR countermeasure systems. The requested items fall into two categories: instrumentation for imaging of etched or ion-sliced ferroelectric surfaces and instrumentation for *in situ* diagnostics of infrared materials being etched or surface passivated in a UHV environment. The instrumentation will be used in a large multidisciplinary laboratory with a proven record of research and collaboration with DoD laboratories and industries.

a) Diagnostics of Surface Quality or Morphology

Surface morphology is a crucial property of a processed electronic material. High quality device performance or multistep processing steps require smooth surfaces of the processed sample. In addition, the presence of a distinctive morphology on processed material often is an important indicator of the basic physics of a new processing technique and thus its measurement can lead to improved processing conditions. As a result, we are requesting funds to purchase an ambient AFM. Our choice of instrument, the Park Nanoscope E with AFM head has an electronic package which is an industry standard and which may be upgraded into an ambient STM or used later with other STM equipment. At present our laboratory has no AFM/STM instrumentation.

b) *In situ* Diagnostics of Dry Etching or Passivation

The development of new UHV processing techniques, e.g. dry etching or surface passivation or reoxidation, requires frequent use of diagnostics mounted *in situ* in the processing chamber. These diagnostics are for chemical diagnostics of the chemistry of both the processed surface and the processing gas. Both "phases" are crucial for achieving proper processing conditions and for improving the chemical state of the processed surface. In this proposal, we are requesting the funds to purchase a state of the art Auger spectroscopy system for chemical examination of products and contaminants on etched and ion-sliced surfaces and a residual gas analyzer for examining the gas-phase products of the reagent etch or passivation gases. Finally we are requesting a Kelvin Probe for measuring band bending (or surface pinning) on etched semiconductor surfaces. In the case of the former, we do not have such tools available for use in our processing systems, while in the case of the latter no Kelvin probe is currently in our laboratory.

II. Supporting Information

A) Technical Description of the Instrumentation

The proposed instrumentation will consist of four separate instruments - each having a unique capability for diagnosing advanced methods of materials processing for infrared and optoelectronic devices:

1) Atomic force microscope - This instrument will have the capability for probing the surface topography of an etched or otherwise processed sample at the Angstrom level. The instrument will operate by "contact mode" probing and will have a full display for recording surface images at the resolution selected. The instrument can be easily upgraded to scanning tunneling microcopy in the future. The AFM will be used to examine the surface morphology of devices at the high level of detail necessary to allow us to establish correlations between nanomorphology and etching/processing parameters and device performance.

2) Auger surface spectroscopy - This instrument incorporates an electron gun and cylindrical electron energy analyzer to probe the chemical composition of a crystal surface. This technique is the method of choice for analyzing surface chemistry after, say, the etching of a semiconductor wafer. The spectrometer in question is capable of examining an area on the order of a few tenths of a mm^2, and detecting a variety of chemical elements at the level of a few percent of a monolayer.

The instrument is bolted onto to a chamber via an ultrahigh vacuum translation stage which is necessary to retract the spectrometer far from the processing area in the chamber. This heavy duty UHV translation stage will be necessary to provide for the mounting of the Auger spectrometer to the existing apparatus. As the existing chamber houses other processing tools and diagnostic probes, the additional degree of translation provided by the stage is required to withdraw the spectrometer from the interaction region when it is not in use. A gate valve will

provide the means for isolating two existing chambers. The valve will allow the diagnostic chamber to be held under UHV while the isolated chamber is at atmosphere. This function is necessary for enabling the rapid exchange of samples that will be important in this study as samples will often be prepared *ex situ* and introduced into the UHV chamber.

3) Residual gas analyzer- This instrument is a small mass spectrometer which may be moved portably from chamber to chamber. It is used to detect the gas composition in the chamber at > 10^{-14} torr level. Typical uses are to monitor the purity of a flowing gas system, to detect contaminants or leaks in a processing chamber, and to analyze the composition of desorbed gas from a thermal desorption system. The spectrometer is capable of operation in ambients ranging from 10^{-4} to 10^{-14} torr, has a mass range of 1–300 amu, and a resolution of better than 1 amu at 5% of peak height.

4) Kelvin probe - This instrument is used to measure the surface voltage on a conducting or semiconducting samples. It is an ideal tool for examining changes in workfunction induced as a result of a processing step or adsorption of polar species. This device is designed to function in ultrahigh vacuum, and thus will enable *in situ* work-function-change measurements. The sensitivity of this probe is ~ 0.1 meV, typically corresponding to an adsorbate coverage of 10^{-3} of a monolayer. The Kelvin probe is completely non-damaging, and, thus, may be used to monitor processing of samples/devices that may be later used/tested *ex situ*.

B. Contribution to Research Currently Funded by the DoD
1. AFOSR/DARPA Program on "New Techniques for Heterogeneous Integration for Sensing Systems"- (F49620-99-1-0038) Dr. Howard Schlossberg

The goal of this program is to use beam induced processes such as ion or electron bombardment, as the basis for new methods of fabrication of new optical structures or devices. Currently two processes are under investigation: Crystal ion slicing and high-resolution etching.

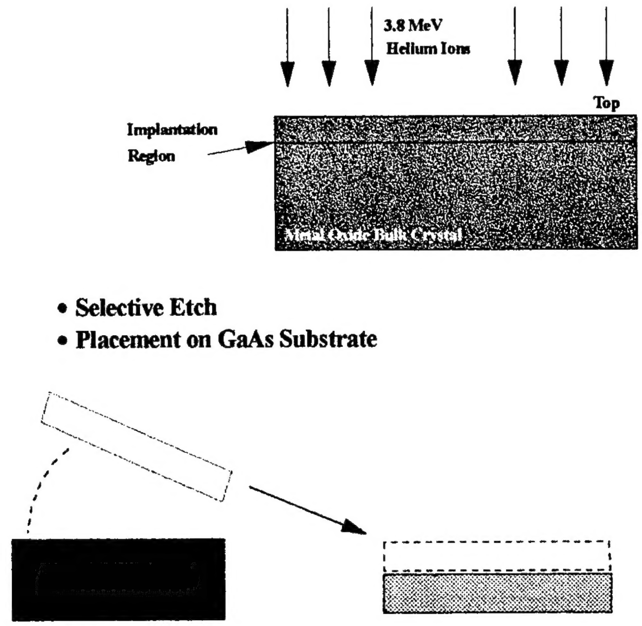

Fig. 1: Sketch of the CIS process for obtaining thin (1-10 μm) single-crystal, stoichiometric films of ferroelectrics or other metal oxides

First, we have recently developed the technique of crystal-ion slicing (CIS) to a lift-off technology for free-standing crystal thin films of metal oxides. This technique (see Fig.1) presents a new approach for truly heterogeneous integration of radically different types of thin-film technology; it can be used to "slice-off" thin films of $LiNbO_3$ for use in modulators or high-dielectric thin films of ferroelectrics for use in uncooled IR detectors. Second, we are developing new plasma-based methods for high-resolution dry etching of GaSb-based materials. This work stems from an increasing need for a well-characterized approach to high-resolution etching of GaSb-based materials. Thus, dry processing of this materials system is a relatively unexplored subject, despite its importance in many new lasers and electronic devices. Either photolithography, laser-write lithography, or electron-beam writing can be used to pattern the surface for these studies. To aid in these studies we have also developed a novel probing technique based on carbon nanotube atomic force microscopy, in collaboration with Prof. George Flynn's group. This technique can be used to characterize the etch-feature morphology for ~

100 Å scale features. In the sections below, we give the specific motivation and more details on our research in this area.

a. Patterning of GaSb-based Semiconductors for Mid-IR Sources

i.) Rationale

Mid-IR lasers with wavelengths from 2-5μm have been a major long-term research goal for Air Force and Army applications in IR countermeasure systems. Recently both optically pumped and direct diode-laser-pumped GaSb-based systems have been found to be attractive for this application, and in fact, the author of this proposal has been active in interacting with the Phillips-Laboratory-funded program at MIT Lincoln Laboratory in this area. Because these sources are broadly tunable throughout the mid-IR, a region containing an atmospheric window as well as many molecular absorptions, these sources are also potentially useful for atmospheric sensing and detection. These same materials have applications for other research areas in electronics and microwave sources.

Both optical and electronic systems of GaSb-based materials require the ability to integrate both active and passive components in the systems. To fabricate these integrated systems requires an etching process for pattern transfer. This process must form precisely defined feature size with well-characterized surfaces. An excellent example of the tolerances needed for these components are those for multimode interference devices, see Figure 2, which are used for signal distribution on some form of wavelength routers, which can be used to combine multiple IR wavelengths. In these devices the width tolerances are extremely tight, device widths must be ±100-200nm for example.

elimination of wall roughness by adjusting the ion-etch chemistry is the use of a frequently used high resolution diagnostic of the surface morphology after each etch step; hence, our request for an AFM in this instrumentation proposal.

Dry etching of GaSb is much less explored despite the widespread emerging interest in its applications for Mid IR applications (see, however, recent experiments using CAIBE etching described in Ref.12). The issues in developing etching for this material are the fundamental chemical and surface characterization of etched materials with different doping levels and alloy concentrations. In addition, as in the case of etching AlGaAs/GaAs, etching of GaSb materials containing aluminum or indium is particularly hard since their etch products are not volatile thus leading to rough surface morphology. In this case, variations in substrate temperature and reactant species need to be examined as ways to alleviate product surface accumulation; our early results in this regard, as shown in Fig. 3, are encouraging. The ultimate goal of the work will be to fabricate, by surface masking followed by pattern transfer, passive wavelength and active devices for applications.

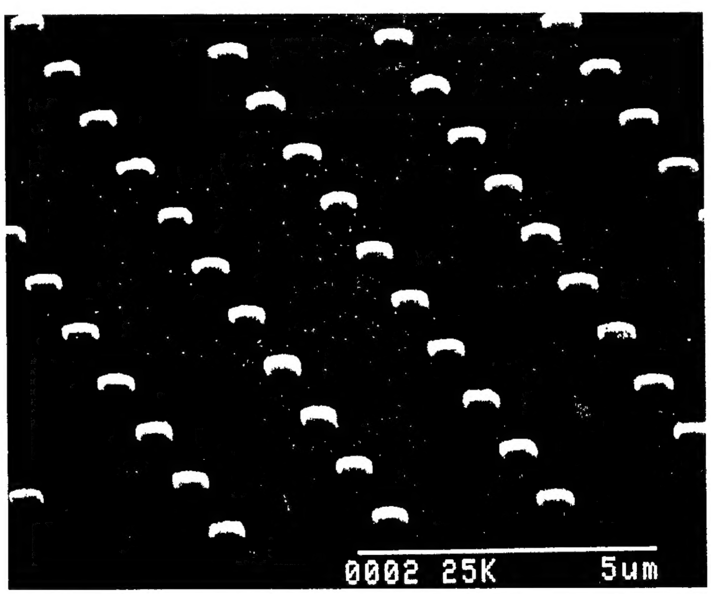

Fig. 3: GaInAsSb/AlGaAsSb multiple quantum well structures etched with ECR plasma

ii) Recent Results:

a) High Resolution Etching of GaSb-based MQW Structures

High resolution and anisotropic dry etching of quantum confined structures is a desirable processing technology in the GaSb-based semiconductor system; unfortunately, in comparison to other compound semiconductor systems, there is only very limited knowledge of GaSb MQW processing science. Thus, we have recently initiated a collaboration with George Turner of MIT Lincoln Laboratory to investigate etching of this system. The study utilizes electron beam lithography and metal lift-off process to fabricate submicrometer features on GaSb as well as AlGaAsSb/GaInAsSb multiple quantum well structures. These provide test structures for our studies by allowing fabrication anisotropy to be observed as a function scale-size. In the first set of experiments, the patterns were transferred into the semiconductor using chemically assisted ion beam etching (CAIBE) with chlorine as the reactive gas in the presence of bombardment by Ar^+ ions of 400-900 eV energy. Cr masks were used with GaSb the substrate, and were found to exhibit good etch selectivity and smooth, highly anisotropic structures were realized. The measured etch rate was successfully fitted to a model of chlorine-based chemically assisted ion beam etching that assumes the formation and desorption of trichloride etch product species.

In a subsequent study photoluminescence of etched features in AlGaAsSb/GaInAsSb were measured after variation in substrate bias and gas composition for CAIBE etching. The dependence of etch damage on incident ion energy was studied using photoluminescence spectroscopy, at 4K. The results indicated that while CAIBE produces high quality etched features, CAIBE at all energies generated etch damage. As a result we have recently investigated ECR plasma etching using chlorine and methane based etchants and found minimal process damage process with an acceptable etch rate for GaSb-based semiconductors. In this system, both surface morphology and damage were found to depend sensitively on the reactant gas composition.

b. Hybrid Integration for RF, Lightwave Components: Crystal Ion Slicing and Wafer Bonding of Thin-Film Single-Crystal Metal Oxides

i) Crystal Ion Slicing - Method and Motivation

The formation of single-crystal thin films for several metal oxides on a substrate surface is important for several areas of integrated optical devices for applications in RF photonics. While progress on vapor-phase or LPE growth of these thin-film materials continues, another approach has recently been invented at Columbia, for obtaining very high-quality, thin metal-oxide films. This approach is the crystal ion slicing (CIS) technique (see Ref. 6 and 15) shown in Fig. 1. Initially a bulk crystal or LPE, MBE or MOCVD grown layer is exposed to a flux of high-energy light-weight ions, typically He+. The use of deep, high-energy implantation results in a change in the reactive chemistry of a deeply buried sacrificial layer such that the top, undamaged thin film can be "sliced off" by exposure to a selective etching solution. The sliced film is then carefully placed onto and bonded to the desired platform substrate via one of a variety of methods including natural Van der Waals forces, chemical adhesive, or metal thin film, where the choice depends on the desired application.

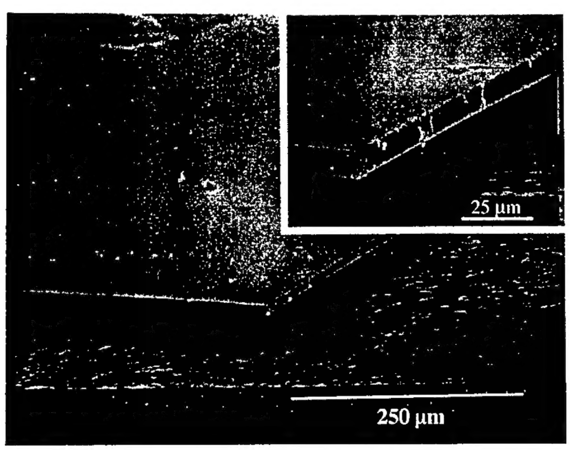

Fig. 4: Fully "sliced," free-standing sample of a CIS $LiNbO_3$ film

Within the last year, we have shown that this technique can be used for fabrication of micrometer thick films of crystals of interest for electro-optics applications. Specifically, we have "sliced" off a 5-9μm film of $LiNbO_3$ with excellent surface morphology, an example is

shown in Fig. 4. Because of its relative degree of chemical inertness, careful investigation of the 10n-induced chemical reactivity of $LiNbO_3$ samples was needed before proper damage-selective etching was achieved. Separate collaborative experiments with Prof. Cross's group at Penn State have shown that the sliced films have bulk-like dielectric properties. This is an extremely important finding since most artificially grown metal-oxide (ferroelectric, PZT, etc.) films have dielectric constants far below those of single-crystal material either due to lack of stoichiometry or to polycrystalline structure. Their linear optical properties have also recently been tested and have been found to be of excellent quality.

In order to obtain good samples, a careful set of experiments were designed to find the right combination of implantation species, dose, and temperature. For example, in the case of $LiNbO_3$, the major concern was in developing a suitable rapid undercut chemistry. Finally, careful testing of the thin-film properties was undertaken. Thus, we have done extensive characterization of the films using optical probing and microscopy, electron microscopy, and x-ray microdiffraction at Columbia.

The sliced films have been bonded onto a variety of surfaces including Si, or SiO_2 and GaAs and the physical properties of the film then compared to those of the bulk crystal. The quality of the bonded films was excellent since they have sharp facets, devoid of microcracks. Extensive research was required to develop this procedure for such crack-free films since contending with as-grown internal stress in the film as well as the stress encountered during the etching process is a major issue in development of the technique. Similarly good facet preparation also requires a careful sequence of processes such as polishing, cleaving, etc.

ii) Recent Progress in Crystal Ion Slicing

- Materials Preparation

We have just shown that a large etch-selectivity enhancement in CIS epitaxial liftoff of He+ -implanted single-crystal lithium niobate ($LiNbO_3$) films can be achieved by rapid thermal

annealing of the samples prior to etching. This heat treatment is found to reduce the time needed for film detachment by a factor as large as 100. Large ($0.5 \times 1 cm^2$) 5 to 10μm-thick single-crystal $LiNbO_3$ films of excellent quality can now be detached in just a matter of a few hours.

- Wafer Bonding of CIS Films to Semiconductors

We have developed direct wafer bonding between helium-implanted metal oxide crystals and various semiconductor platforms. The strength of the bond has been studied in terms of shear stress and found to be comparable to that of Si-to-Si bonding (≥50%) in all cases. Hydrophilic surfaces yield strength improvement with temperature. A de-bonding threshold temperature between 400°C and 500°C is related to the interfacial bond rigidity under conditions of thermal stress. Strength enhancement results from short-time thermal treatment.

- Frequency Nonlinear Power Conversion in CIS Films

We have demonstrated optical frequency mixing in epitaxial liftoff thin films of single-crystal $LiNbO_3$ integrated onto heterogeneous planar glass platforms. These films were found to have a nonlinear optical response comparable to that of the bulk. Second-harmonic generation is investigated as a function of crystal orientation, ion implantation, and modal and temperature dispersion. Ion implantation-induced shifts in the refractive indices have been shown to be useful for achieving phase-matching at 1.55 μm at lower temperatures than those required in bulk materials.

- Ultra-thin Modulator Material for High Performance Devices

We have recently demonstrated that electro-optic modulation can be obtained in (10μm-thick) single-crystal $LiNbO_3$ films obtained by crystal-ion-slicing (CIS). This is an important step in using these films for heterogeneous device integration, and perhaps even more important, we have completed detailed numerical modeling, which shows that these films can be used for making new forms of low V_π analog RF/optical links. Our just completed measurements show

that the electro-optic response of these films is comparable, within experimental error, to that of the single-crystal bulk $LiNbO_3$ and is vastly superior to the previously reported values for epitaxial polycrystalline thin films. The product of half-wave voltage and modulator length, $V_\pi L$, is 8 Vcm. Post lift-off annealing (PLA) is shown to be of key importance in improving the modulator extinction-ratio.

2. Use in Other DoD Programs: AFOSR/MURI Program R522626 9101 on "Integrated Optical Components," Lt. Col. Gernot Pomrenke

a. On-chip Optical Isolators

Because of the requirement for multiple interfaces and long free-space diffraction paths, integrated versions of optical isolators have been difficult to realize and the leading work has thus far been done abroad. Our work on this MURI program has examined both theoretically and experimentally the issues involved in designing and fabricating an integrated isolator structure. Several alternate designs have been considered including a hybrid design using a conventional single optical path, a Mach Zehnder design, and a simplified single-path structure using recently developed magnetized YIG material. The Mach-Zehnder-based design is attractive because it avoids the use of free-space path lengths as well as the need for cross polarizers; however, it does require long low loss guided light paths. At present we are developing the low-loss waveguides needed for this approach. We have also carried out initial tests using an optical fiber version of the Mach Zehnder isolator and have observed large non-reciprocal phase shifts in BiYIG waveguides. This is a major research accomplishment since it is the first observation of optical isolation and since the Mach-Zehnder structure allows the elimination of some of the polarizing elements discussed below. As just indicated, the quality of the etched YIG surface plays a crucial role in controlling the optical loss in the YIG waveguides needed for the Mach-Zehnder device. The instrumentation requested here would provide the surface probes needed to improve the etch process.

b. CIS Films for Optical Isolation

CIS technology has been recently, successfully, demonstrated to yield very high-quality thin films of epitaxial YIG, “sliced” from an LPE layer grown on a gadolinium gallium garnet (GGG) substrate. Figure 5 shows a YIG layer after implantation and selective etching, i.e. in the midst of the "slicing" procedure. Notice the sharp delineation in the selectively etched region as well as the undamaged properties of the facet. The top surface also remains undamaged. To obtain an excellent surface quality, we have also developed a procedure based on rapid thermal annealing which enables removal of residual implant damage in the top of the sliced film without annealing out of the damage in the lower heavily implanted region that must remain intentionally damaged for the efficacy of the CIS technique.

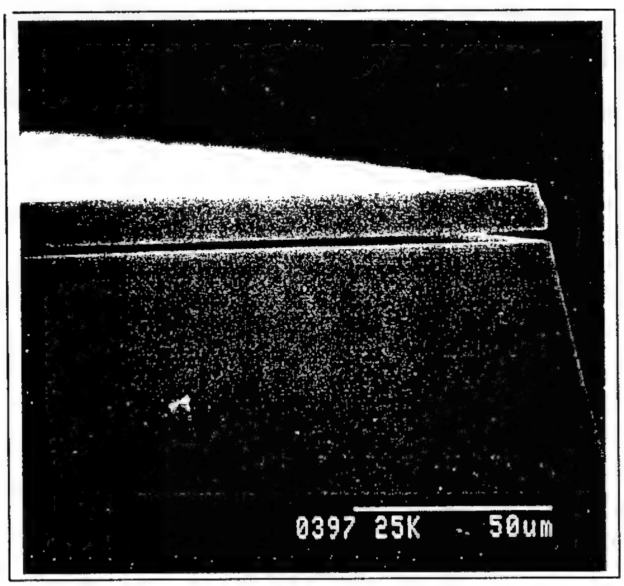

Fig. 5: Side-view of a partially “sliced” sample of single-crystal YIG. The YIG was grown by LPE on a GGG substrate.

We are currently attempting to design isolator structures that use CIS films. One approach would mount the film on a $LiNbO_3$ surface waveguide, in order to subject the evanescent wave to Faraday rotation in the CIS film, while still allowing the majority of the light

to propagate in the $LiNbO_3$ film. The surface quality of the CIS YIG film would play a crucial role in the performance of such an isolator.

C) Interfacing and Upgrading of Other Research Facilities Now Available

The instruments to be purchased through this proposal will also interface to a wide range of electronics materials instrumentation in Prof. Osgood's Laboratories at Columbia. These instruments include: 1) Systems for research on UHV growth of thin interfacial layers for epitaxy of thin films on Si substrates; 2) Numerous stations for investigating the basic surface chemistry of semiconductor and metal surfaces; 3) Instruments for lithographic patterning of electronic materials including those based on optical, laser, and e-beam lithography. Finally, and most important, the requested instrumentation will provide a crucial new diagnostic capability for the full range of etching tools, that are used in the laboratory, including electron, ion, and plasma based systems.

The requested instrumentation will be central to our DoD research, described above, as well as other research carried out in the laboratory. For example, a recent project involved etching InP photonic devices, which were patterned with our laser lithography system (see Fig. 2); thus the project required examination of the surface morphology of the etched devices. In such an application AFM measurements are crucial for imaging the surface topography. Similarly recent studies in our laboratories on the chemistry of self-assembled monolayer films on GaAs surface used for high-resolution patterning required the use of a chemically sensitive probe to examine the surface after desorption of the SAM. In this case, it was essential to have an Auger surface probe to use for examining the GaAs surface. Similar arguments apply to many other projects in the laboratory.

Finally, it is important to point out again that this instrumentation would provide the first access in our laboratory to AFM and Kelvin probes. This instrumentation would thus significantly upgrade the overall laboratory capability in surface probing of processed materials.

D) Amounts and Sources of Ongoing Research

1) Primary Research -
AFOSR/DARPA, F49620-99-1-0038, "New Techniques for Heterogeneous Integration for Sensing Systems"
11/15/98 - 11/14/01 - $ 430,000 per year (first year)

2) Secondary Research -
a) MURI/AFOSR, UMINN R522626 9101, "New Integrated Optical Components for Broadband Optical Communication Systems"
3/31/99 - 4/1/01 -$250,000 per year

b) JSEP, DAAG55-97-1-0166, "Extending the Useful Range of the Electromagnetic Spectrum"
10/30/98-10/14/99 - $ 61,873 (This includes a project on high-resolution III-V etching science)

E) Training of Future Scientists and Engineers in Areas Relevant to the DoD

The work supported in the above programs is essentially experimental applied physics with the primary emphasis on optical and electronic materials. This is an area relevant to the DoD for the technologies needed for current and future DoD systems. For example, the materials studied here are at the heart of high-speed RF/optical links as well as in many optical sensors and probes.

The best indication of how the students trained in such areas are utilized is to consider the jobs and careers that funding by the Department of Defense of the research group of the principal investigator at Columbia have filled. This information is supplied below for a representative sample of the students and postdocs in the Columbia group:

Khalid Khan	Electronics Technology (Tigress Technology)
David Levy	Optical Systems (Lucent)
Peter Lasky	Semiconductor Processing Technology (McKinsey Phillips)
Igor Ilic	Communications Technology (Boston Consulting)
Roberto Paiella	Optical Devices (Research Scientist, Lucent)
Vladimir Bulovic	Optical Devices (Professor, Rutgers University)
Louay Eldada	Optical Devices and Interconnects (AlliedSignal Corp.)

Michael Freiler	Semiconductor Processing (Sematech)
Q.Y. Yang	Semiconductor Device Fabrication (IBM)
Alan Willner	Telecommunications Systems (Professor, USC)
Jim O'Neill	Silicon-Devices and Fabrication (IBM)
Robert Krchnavek	Optical Interconnects (Professor, Rowan State)
Ping Shaw	Optical Sensors (NIST)
Dragan Podlesnik	Plasma Processing Executive (Advanced Materials)
Zhong Lu	Plasma Processing Engineer (Motorola)
William Holber	Plasma Processing Executive (ASTeX)
Tom Licata	Process Engineering Manager (Motorola)
Zhen Wu	Physics of Optical Surface Interactions (Professor of Physics, Rutgers)
Ted Cacouris	Processing Engineer (Novelus)
Julian Chen	Display Technology (IBM-T.J.Watson Laboratories)

Many of these, as well as other students, continue to be involved in DoD research and development programs. In addition, we have traditionally had a high involvement of undergraduate students in our laboratories during the regular academic year and summer vacation period. These students have typically become involved in experimental work using equipment such as that described above. Finally, virtually all graduate students involved in research on integrated optics in the Osgood group have frequent contact with industrial research, including that at Allied Corp., AT&T, Lincoln Laboratory, and IBM.

F) Lifetime and Maintenance of Equipment

The equipment will have an estimated lifetime of 10 years; this lifetime is based on the lifetime of similar equipment at Columbia. The instrument will be located in a new laboratory in the Schapiro CEPSR Building on the Columbia main campus. The equipment will be maintained by the postdoctoral research fellow who is assigned to work on the instrument. In addition, as is needed, items in need of repair will be serviced by the original vendors or at the in-house electronics shop.

G) Industrial Collaborators

An important part of our work in electronic device processing has been collaborations with nearby government and industrial partners. For example, in the past we have benefitted

significantly in our work on semiconductor processing via collaboration with groups at ARL, IBM, and ASTeX. In fact, the work described here on etching of III-V materials is a collaboration with George Turner, Gp83, at MIT Lincoln Laboratory, who contributes high quality materials and discussions on potential DoD applications. Clearly the attainment of an enhanced experimental capability via the present proposal would enable us to offer a stronger research capability for future collaborative interactions.

H) Background of the Principal Investigator

The instrument to be purchased will be used in the laboratory of Professor Richard Osgood. Professor Osgood's laboratory is a leading research facility in both fundamental science and applications of semiconductor surface interactions. In the last few years, Prof. Osgood's research has continued to involve research on new semiconductor and ferroelectric materials and their applications in device technology (see Appendix A). The work described in this proposal is also connected with research in his laboratory on more basic studies of materials surface chemistry and physics.

Appendix A: Recent Publications Relevant to this Proposal

The following papers present the recent work done at Columbia directly related to the present proposal:

1. J.Z. Huang, R. Scarmozzino, G. Nagy, M.J. Steel and R.M. Osgood, Jr., "Realization of a Compact and Single-Mode Optical Passive Polarization Converter," submitted to IEEE Photon. Technol. Lett. (July 28, 1999).

2. A.M. Radojevic, M. Levy, H. Kwak, and R.M. Osgood, Jr., "Strong Nonlinear Optical Response in Epitaxial Liftoff Single-Crystal $LiNbO_3$ Films," submitted to Appl. Phys. Lett. (1999).

3. T.A. Ramadan, R. Scarmozzino, and R.M. Osgood, Jr., "A Novel 1x4 Coupler-Multiplexer Permutation Switch for WDM Applications," submitted to J. Lightwave Tech. (June 1999).

4. J. Fujita, M. Levy, R.U. Ahmad, and R.M. Osgood, Jr., M. Randles, C. Gutierrez, and R. Villareal, "Observation of Optical Isolation Based on Nonreciprocal Phase Shift in a Mach-Zehnder Interferometer," accepted for publication in Appl. Phys. Lett. (1999).

5. H. Rao, R. Scarmozzino, and R.M. Osgood, Jr., "A Bidirectional Beam Propagation Method for Multiple Dielectric Interfaces," accepted for publication in IEEE Photon. Technol. Lett. (1999).

6. A.M. Radojevic, M. Levy, R.M. Osgood, Jr., K. Atul, H. Bakhru, C. Tian and C. Evans, "Large Etch-Selectivity Enhancement in the Epitaxial Liftoff of Single-Crystal $LiNbO_3$," Appl. Phys. Lett. 74, 3197 (1999).

7. D.S. Levy, K.H. Park, R.Scarmozzino, R.M. Osgood, Jr., C. Dries, P. Studenkov, and S. Forrest, "Fabrication of Ultracompact 3dB 2x2 MMI Power Splitters," IEEE Photon. Technol. Lett. 11, 1009-1011 (1999).

8. J. Fujita, M. Levy and R.M. Osgood, Jr., "Non-peripheral Cleaved Facet Fabrication Technique," IEEE Photon. Technol. Lett. 11, 78 (1999).

9. F.J. Rachford, M. Levy, R.M. Osgood Jr., A. Kumar, and H. Bakhru, "Magnetization and FMR Studies in Implanted and Crystal Ion Sliced Bi-YIG Films.," J. Appl. Phys. 85, 5217-5219 (1999).

10. J.Z. Huang, R. Scarmozzino and R.M. Osgood, Jr., "A New Design Approach to Large Input/Output-Number Multimode Interference Couplers and its Application to Low-Crosstalk WDM Routers," Photon. Technol. Lett. 10, 1292 (1998).

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